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TWO YEARS OF ON-ORBIT GALLIUM ARSENIDE PERFORMANCE FROM THE LIPS SOLAR CELL PANEL EXPERIMENT

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An analysis of the LIPS on-orbit performance of the gallium arsenide panel experiment is presented from flight operation telemetry data. Raw data, obtained from the NRL, was culled to preclude spurious results from large sun angles, shadowing, and measurements made on a cold array. Algorithms were developed by; and computerized at The Aerospace Corporation to calculate the daily maximum power and associated solar array parameters by two independent methods. The first technique utilizes a least mean square polynomial fit to the power curve obtained with intensity and temperature corrected currents and voltages; whereas, the second incorporates an empirical expression for fill factor based on an open circuit voltage and the calculated series resistance. Maximum power, fill factor, open circuit voltage, short circuit current and series resistance of the solar cell array are examined as a function of flight time. Trends are analyzed with respect to possible mechanisms which may affect successive periods of output power during two years of flight operation. Degradation factors responsible for the on-orbit performance characteristics of gallium arsenide are evaluated and discussed in relation to the calculated solar cell parameters. Performance trends and the potential degradation mechanisms are correlated with existing laboratory and flight data on both gallium arsenide and silicon solar cells for similar environments.

INTRODUCTION

The normally passive plume shield for a spacecraft upper stage rocket has been modified to incorporate an active payload by the Naval Research Laboratory. Partly in humor, the resulting satellite was named "Living Plume Shield," and the acronym "LIPS-II" has been widely embraced. An artist's rendition of the satellite is shown in Figure 1. The outer diameter of the body is 188cm (74 in.), and the inner diameter 142cm (56 in.). Maximum body thickness is 10cm (4 in.) at the inner ring and tapering to 38mm (1.5 in.) at the outer edge. The three solar array panels have solar cells mounted on both

sides and these provide the power generation capability to the spacecraft. One side of one panel contains 300 (2cm x 2cm) gallium arsenide (GaAs) solar cells while each of the other five sides contain 104 (2cm x 6cm) silicon (Si) solar cells. The U. S. Air Force developed GaAs cells were donated to the Navy in a cooperative program to build, test, qualify, and fly a GaAs solar panel.

The solar panels are stowed on the same surface as the antenna and gravity gradient boom, (which are also stowed) during launch and upper stage burn, and therefore protected from the rocket plume impingement. Shortly after the upper stage burn, LIPS-II is separated and is a free satellite in approximately circular orbit at 600nm with a 63° inclination. Antennas and solar panels are deployed and the satellite is subsequently despun and gravity gradient stabilized. As shown in Figure 1, the antenna and gravity gradient boom are earth pointing, providing stability in pitch and roll, but allowing freedom in yaw, damped only by hysterisis rods, which couple to the earth's magnetic field.

GaAs Panel Design

The GaAs solar cells were designed and fabricated by the liquid phase epitaxy (LPE) process developed by Hughes Research Laboratory, Malibu, under contract to the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories. The cells were transferred form the Air Force and assembled into a flight panel by Spectrolab under contract to the Naval Research Laboratory.

The orbit and experimental description is given in Table 1. Three circuits in parallel each consists of 25 cells in series by four cells in parallel for a total of 100 cells per circuit. The total of 300 GaAs cells has less active area than one Si cell panel surface each consisting of 52 cells in series by two cells in parallel. Both the GaAs and the Si cell panels were designed to produce similar voltages to power the LIPS-II. Figure 2 is a pictoral diagram of the GaAs panel layout.

A sun sensor is deployed diametrically opposite to the GaAs panel on the satellite. It is designed to quantify the deviation between the perpendicular to the GaAs panel and the sun line. This information is needed to accurately evaluate the panel output at other than nominal conditions. Additionally, a thermistor has been imbedded in the aluminum honeycomb panel substrate to sense the temperature of the back of a centrally located GaAs cell. Panel temperature, as indicted by this thermistor, together with the angle of solar incidence from the sun sensor, and intensity variations in the solar constant due to the earth orbit ecliptic are used to normalize GaAs panel data parameters.

EXPERIMENT DESIGN

An electronic experiment control package was designed and fabricated which allows the GaAs panel to contribute its power to the LIPS-II bus under normal conditions, and be commanded into an experiment mode to evaluate the GaAs performance. When activated, the entire 300 cell panel is disconnected from

the bus and electrically cycled through a simulated load sequence. The dwell at each step is approximately one second, during which time, ten data samples are transmitted to the ground station. The first step is an open circuit voltage (V_{OC}) measurement. The second step obtains short circuit current (I_{SC}). In actuality, the value is slightly off true Isc due to diode and line voltage drops. The third returns to V_{OC}. The fourth through seventh steps measure both current and actual voltage at approximately 22, 20, 18, and 16 volts. These step points were chosen to permit close evaluation of the current-voltage curve from beginning to end of life and under varying intensity conditions where voltage variations are second order effects. The eighth and final step of the experiment, returns the panel to the bus.

It is noted that the angle from the panel normal to the sun line and panel temperature are also in the telemetry with the panel electrical parameters.

DATA ACQUISITION AND REDUCTION

Once LIPS-II was in orbit, all telemetry and data are acquired in real time at NRL's Blossom Point Satellite Tracking and Command Station in Maryland. Typically the station "sees" LIPS-II for seven passes each day with varying pass duration up to about 20 minutes long. During those times, the sun angle is monitored, and if the sun line is within 45° of normal to the GaAs panel, the experiment is activated. Up to three activations of the experiment per pass are commanded if the sun conditions are acceptable. On many passes, no data at all is taken, since the satellite is free in yaw and its position relative to the sun cannot be controlled. Further, the ground station position relative to the satellite orbit may be unfavorable for an extended period, with passes occurring predominately at night when satellite eclipsing is likely. This condition may last for days until the satellite orbit precession and earth movement around the sun again produce favorable conditions for the experiment. Unfortunately, one of these extended data outages occurred for the first 30 days after launch, and beginning of life data was therefore lost.

Once data is acquired by the tracking station, it is converted to report form by an off-line data reduction and correction program. Current, temperature, and sun angle information are reported as received; voltages are corrected for diode and line drops and then reported as a raw value. A second data set is then generated by the Aerospace Computer Program, correcting the raw currents and voltages for intensity and temperature. The cosine of the angle to the sun and the solar constant correction as well as the appropriate temperature coefficient corrections are used to modify both current and voltage values. The temperature coefficients, α and β, used for current and voltage correction (Ref. 1) are 3.9×10^{-5} Ampere/°C and -2.04×10^{-3} Volt/°C, respectively. Raw telemetry data is normalized to 28°C and a solar insolation of 135.3×10^{-3} Watts/cm^2 (AMØ) normal to the panel surface.

Algorithms and a computer program (Ref. 2) were developed to obtain the normalized daily maximum power by two independent techniques (Ref. 3). The computer program discriminates against telemetry requiring large corrections for data normalization. This minimizes mathematical error from raw telemetry requiring large extrapolation. Therefore, temperature

correction is limited to between 0° and 50°C; sun angle between 0° and 25°; and percent allowable deviation from the ten previous calculated power data points to less than 15%.

After the telemetry voltages and currents are normalized, the two algorithms separately calculate the maximum power output for each revolution which, in turn, are statistically averaged on a daily basis. The LMS-Method incorporates a fifth order polynomial to approximate the power curve which is then maximized as a function of voltage. The order of the polynomial is excessive, but was used to maintain small deviations in curve fitting.

The FF-Method is based on parametric equations developed from solar cell empirical characteristics (Ref. 4). The pertinent input parameters for this method are open circuit voltage, short circuit current, and the calculated series and shunt resistances. The general equation is,

$$FF = \left(\frac{v_{OC} - \ln (v_{OC} + 0.72)}{v_{OC} + 1}\right)\left(1 - r_S\right) -$$

$$\left(\frac{v_{OC} + 0.7}{v_{OC}\, r_{SH}}\right)\left(\frac{v_{OC} - \ln (v_{OC} + 0.72)}{v_{OC} + 1}\right)^2 \left(1 - r_S\right)^2$$

v_{OC} ≡ open circuit voltage (V_{oc}) divided by (nkT/q)

r_{SH} ≡ shunt resistance (R_{sh}) divided by (V_{oc}/I_{sc})

r_S ≡ series resistance (R_s) divided by (V_{oc}/I_{sc})

For the LIPS-II experiment, calculated panel shunt resistances range between 600-1200 ohms. Therefore, the second term in the above equation is negligible. The fill factor is affected more by the series resistance, however, whose panel values are between 2 and 3 ohms. The above equation for fill factor reduces to:

$$FF = \left(\frac{v_{OC} - \ln (v_{OC} + 0.72)}{v_{OC} + 1}\right)\left(1 - r_S\right)$$

This value combined with the corrected I_{sc} and V_{OC} allows the maximum output power to be calculated.

Results and Analysis

Measurements taken at Spectrolab with an uncollimated xenon lamp prior to shipment of the LIPS-II GaAs solar cell panel gave 24.5 watts at 1 sun (AMØ) intensity and values for I_{sc} of 1.29A, V_{oc} of 25.2V, and FF (fill factor) of 0.76. This beginning-of-life (BOL) power equates to a 15.1% in panel cell efficiency. Figures 3 and 4 show on-orbit panel output power vs. time. BOL

data was not available after panel deployment in orbit, since the ground station position relative to the satellite orbit was unfavorable and eclipsing occurred during satellite monitoring for the first 30 days after launch. On day 32 after launch the GaAs panel's measured power output degraded 6.9% from the value at Spectrolab's facility. Most of the power loss is a result of the I_{sc} degrading by 6.2% (Fig. 5). V_{oc}, FF, and R_s (Figs. 6 through 8) are relatively unchanged during the first 32 days in orbit. It is only conjecture as to the cause, since the actual loss mechanism has not been identified. From day 32 to 550 the power degrades an additional 12.2% and again there is good correlation with it being attributed to the loss in I_{sc}. Again, there is little, if any, change in V_{oc}, FF, and R_s. After day 550, the trend appears to plateau and the power output degrades less. Power has degraded only 0.2 watts (0.8%) from a 2nd order smoothing curve through the daily averaged power measured up to 765 days after launch. Short circuit current has also degraded approximately the same amount with no change in the other parameters (Figs. 6 through 8). Power performance data and the corresponding solar array parameter values for I_{sc}, V_{oc}, and FF are listed in Table 2 for the three successive time periods discussed.

Data in Table 3 give the equivalent electron and proton 1-MeV electron fluences for both Si and GaAs solar cells (Ref. 5) in the 600 nmi/63° space radiation environment. The latter is based on damage coefficients obtained from JPL publication 84-61 (Ref. 6). The total 1-MeV electron fluences calculated for GaAs after 550 and 765 days are 1.82×10^{13} and $2.53 \times 10^{13} e \cdot cm^{-2}$, respectively; whereas, for Si they are 5.48×10^{13} and $7.62 \times 10^{13} e \cdot cm^{-2}$, respectively. According to the "Solar Cell Radiation Handbook" (Ref. 7), Si solar cells with both BSF and BSR will degrade 11-14% and those with only a BSR will degrade 2-4% after a total fluence of $5.48 \times 10^{13} e \cdot cm^{-2}$ (550 days) and a respective 13-16% and 3-6% after a 1-MeV fluence of $7.62 \times 10^{13} e \cdot cm^{-2}$ (765 days). On the other hand, p/n GaAs solar cells with an AlGaAs window layer will degrade 2.0% after $1.82 \times 10^{13} e \cdot cm^{-2}$ (550 days) and 2.5% in power output after $2.53 \times 10^{13} e \cdot cm^{-2}$ (765 days).

Due to the large discrepancy between the observed on-orbit and calculated irradiated GaAs power losses, anomalous power loss factors other than electron and proton radiation can account for such a discrepancy and still maintain a constant fill factor as shown in Fig. 7. These are listed in Table 4 with the observed degraded panel parameters that can account for each. The Air Force Wright Aeronautical Labs (AFWAL), Aero Propulsion Laboratory (APL), has undertaken the investigation of an equivalent GaAs solar cell panel, LIPS-I, that has not flown. The issues raised by the anomalous power loss mechanisms in Table 4 will be addressed as shown in Table 5 by mechanical and thermal stress testing the LIPS-1 panel and special irradiation tests on GaAs and Si solar cells.

Referring back to Table 3, one sees that Si will degrade approximately 2% from day 550 to day 765 after launch (i.e., an incremental $2.14 \times 10^{13} e \cdot cm^{-2}$ at 1-MeV after 550 days of irradiation exposure in low earth orbit). GaAs, how-

ever, will degrade only 0.5% after an additional increment of $7.10 \times 10^{12} e \cdot cm^{-2}$ equivalent 1-MeV fluence after 550 days in orbit. This calculated power loss of 0.5% using the 1-MeV equivalent electron fluence model for GaAs incorporating GaAs damage coefficients is very close to the observed 0.8% power loss (see Table 2) between day 550 and 765 after launch. Apparently the anomalous power loss factors contributing to the large loss in output power from the GaAs panel from launch up to around day 550 after launch have subsided and/or the re-connecting of electrical interconnects and/or thermal annealing of GaAs is starting to take place.

The experimental results of the LIPS-II panel are beginning to look encouraging. Only more orbital telemetry after more exposure to the geomagnetically trapped radiation of space will demonstrate and confirm the projected advantages of GaAs solar cells for primary power applications in a space environment.

Summary and Conclusions

The first two years of on-orbit telemetry from the LIPS II gallium arsenide solar cell panel experiment was evaluated to determine power output performance and degradation vs. time in orbit. The power loss associated with decreasing short circuit current but constant fill factor, open circuit voltage and series resistance during the first 550 days after launch is excessive. The loss is attributed to anomalous optical and/or mechanical panel degradation factors which overwhelm the power output loss due to the electron and proton omni-irradiation environment in free space. During the period following 550 days, a decreasing trend in the power loss rate is observed. This region of power output decay can be described by the 1-MeV equivalent electron fluence model with GaAs damage coefficients inputed for the Si damage coefficients.

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References

1. "A Method for Predicting Solar Cell Current-Voltage Curve Characteristics as a Function of Incident Solar Intensity and Cell Temperature," by J. D. Sandstrom, JPL Technical Report 32-1142, July 15, 1967.

2. "LIPS Gallium Aresnide Solar Array," by M. P. Pennell, The Aerospace Corporation, ATM-83(3524-03)-1, August 10, 1983.

3. "On-Orbit Performance of LIPS Gallium Arsenide Solar Cell Experiment," by T. Bavaro, R. W. Francis, and M. Pennell, Proceedings of the Space Photovoltaic Research and Technology Conference, NASA Publication 2314, pp. 81-89, 1983.

4. "Solar Cell Fill Factors: General Graph and Empirical Expressions," by M. A. Green, Solid-State Electronics, Vol. 24, No. 8, pp. 788-789, 1981.

5. "Solar Cell Radiation Model Computer Program," Aerospace Corporation Power Sources Section, 1985.

6. "Radiation Effects in Silicon and Gallium Arsenide Solar Cells Using Isotropic and Normally Incident Radiation," by B. E. Auspaugh and R. G. Downing, JPL Publication 84-61, September 1, 1984.

7. "Solar Cell Radiation Handbook," by H. Y. Tada, J. R. Carter, B. E. Anspaugh, and R. G. Downing, JPL Publication 82-69, November 1, 1982.

8. Private communication with B. E. Anspaugh, JPL, Pasadena, CA, July, 1984.

LIPS II

LAUNCH DATE:	10 FEB 83
ORBIT:	CIRCULAR
ALTITUDE:	600 nmi
INCLINATION:	63°
ORBITAL PERIOD:	1.8 hr

GaAs Experiment

1-PANEL:	4P x 25S x 3 CKTS
CELLS:	300 EACH (2 x 2 x 0.036 cm), 15.5%
COVERGLASS:	0.03 cm (0.012 in.) FS/UV-FILTER
POWER (BOL):	24.5W AT 30°C

Table 1

Observed GaAs Panel Power Loss

DAYS FROM LAUNCH	P_{MAX} (W)	I_{SC} (A)	V_{OC} (V)	FF
0 - 32	24.5 - 22.8 -6.9%	1.29 - 1.21 -6.2%	25.2 - 24.7 -2.0%	0.76 - 0.78 +2.5%
32 - 550	22.8 - 19.8 -12.2%	1.21 - 1.07 -10.8%	24.7 - 24.1 -2.4%	0.78 - 0.78 0.0%
550 - 765	19.8 - 19.6 -0.8%	1.07 - 1.06 -0.8%	24.1 - 24.1 0.0%	0.78 - 0.78 0.0%
TOTAL	-19.9%	-17.8%	-4.4%	+2.5%

Table 2

Calculated Space Radiation Environment

	FLUENCE-Si (equiv 1-MeV e/cm^2)	FLUENCE-GaAs (equiv 1-MeV e/cm^2)	%PMAX AFTER 550 DAYS	%PMAX AFTER 765 DAYS
ELECTRONS	7.57×10^{11}/yr	6.80×10^{11}/yr	Si 11 - 14%	Si 13 - 16%
PROTONS	3.56×10^{13}/yr	1.14×10^{13}/yr	GaAs 2.0%	GaAs 2.5%

Table 3

Anomalous Power Loss Factors which Maintain Constant Fill Factor

I. SPECTRAL TRANSMISSION LOSS

- DECREASING I_{SC}

II. FAILED-OPEN CELL INTERCONNECTS OR CRACKED/BROKEN CELLS, LEAD TO REVERSE-BIASED PARALLEL CELLS

- PROMINENT I_{SC} DECREASE (reverse cell characteristics control)
- SMALL V_{OC} LOSS

III. LOW ENERGY PROTON OMNI IRRADIATION ON UNFILTERED GaAs CELL AREAS (bus edges and lifted metal contacts)

- DECREASING I_{SC} WITH FLUENCE
- SMALL V_{OC} LOSS WITH FLUENCE

Table 4

LIPS-I Investigation

- ISSUES TO BE RESOLVED AT AFWAL/APL
  - MECHANICAL DEGRADATION STRESS FACTORS
  - THERMAL CYCLING TO STIMULATE ORBITAL CONDITIONS
  - SPECIAL RADIATION EDGE EFFECTS ON GaAs vs Si SOLAR CELLS

Table 5

LIPS II Living Plume Shield

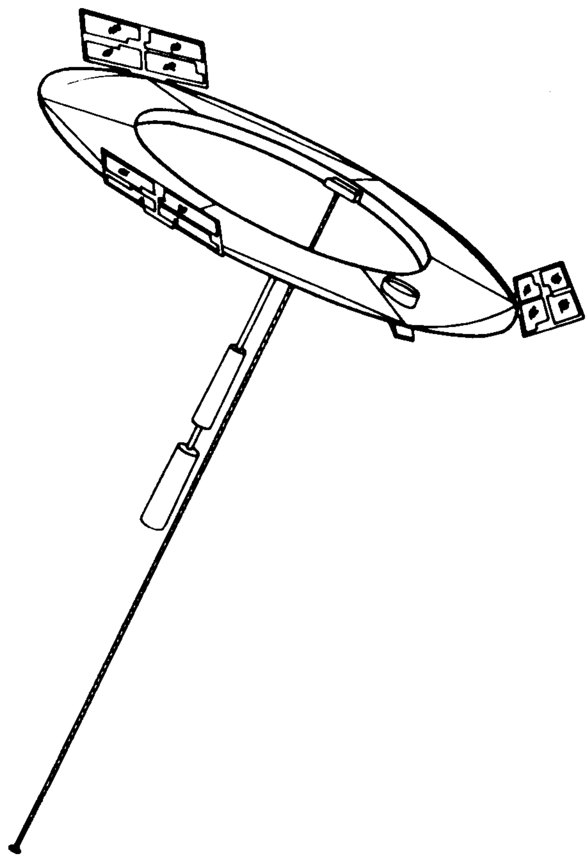

Figure 1

LIPS II Gallium Arsenide Solar Panel Layout

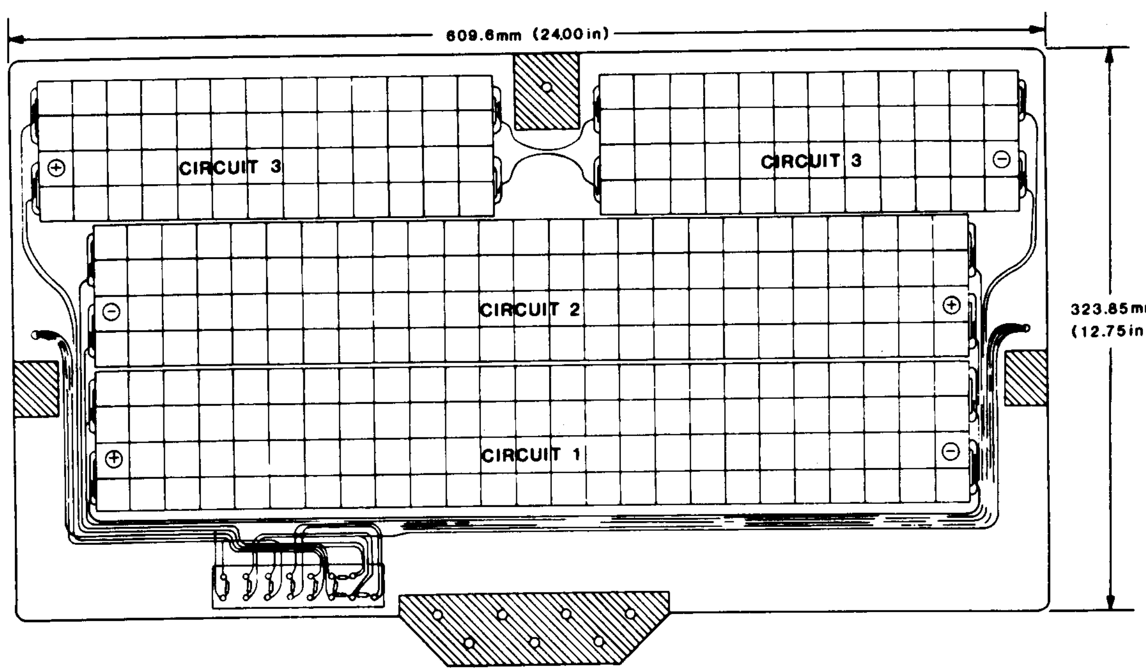

Figure 2

Maximum Power (LMS Method) with Second Order Smoothing Curve vs Days from Launch

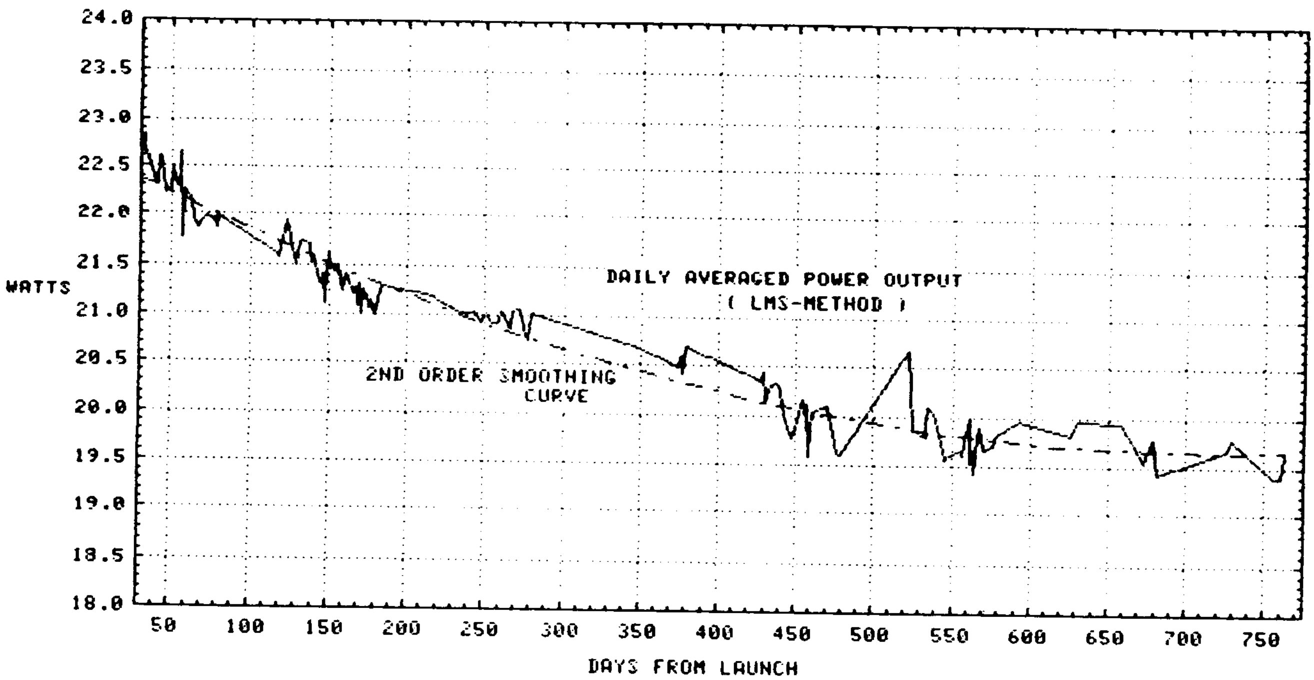

Figure 3

Maximum Power (FF-Method) with Second Order Smoothing Curve vs Days from Launch

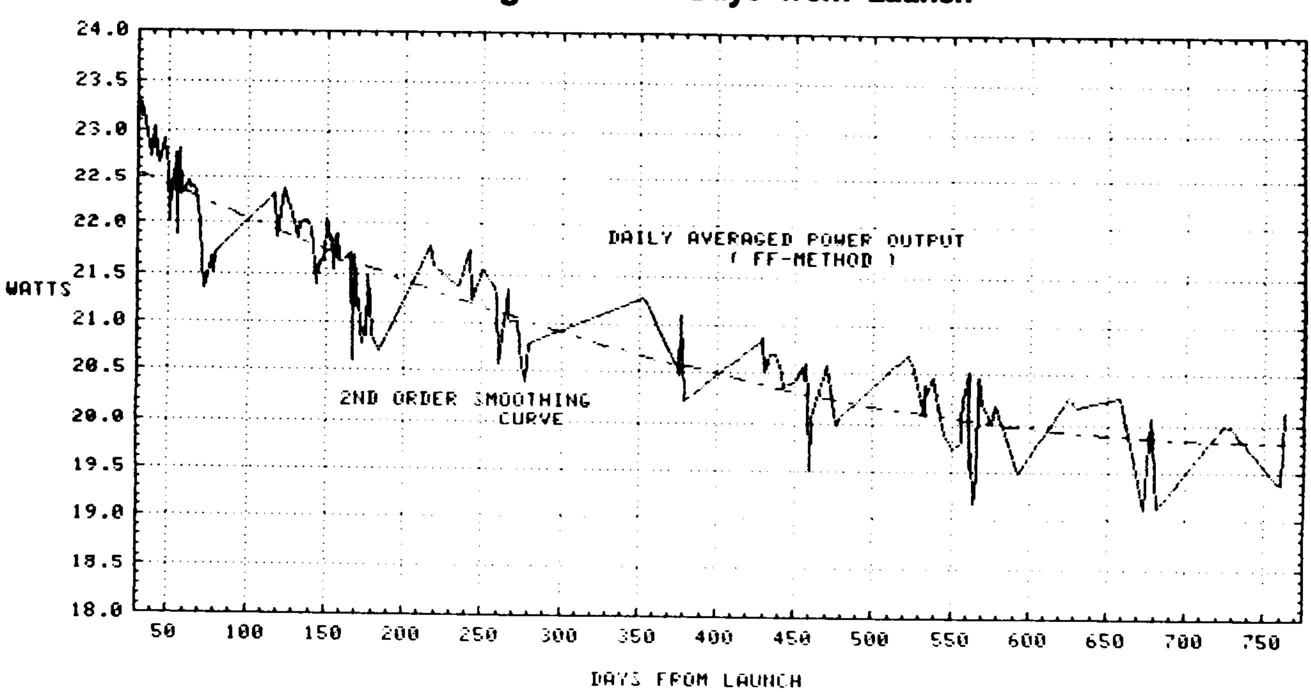

Figure 4

Short Circuit Current vs Days from Launch

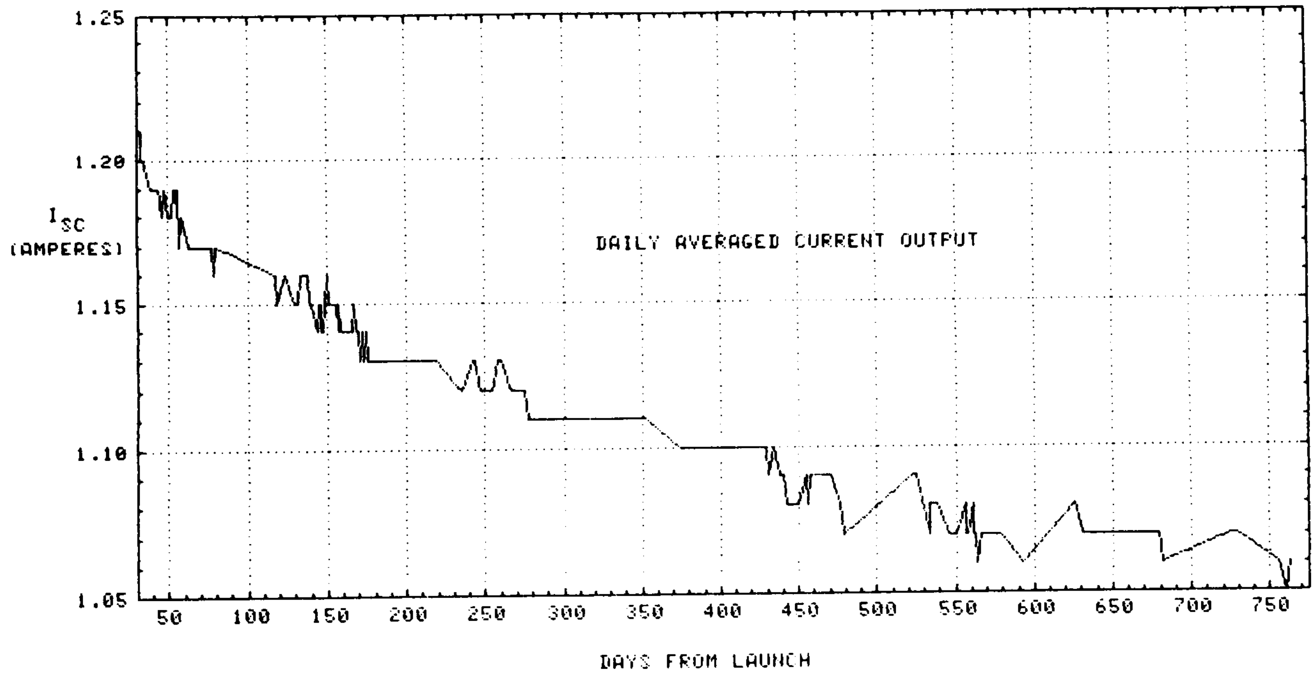

Figure 5

Open Circuit Voltage vs Days from Launch

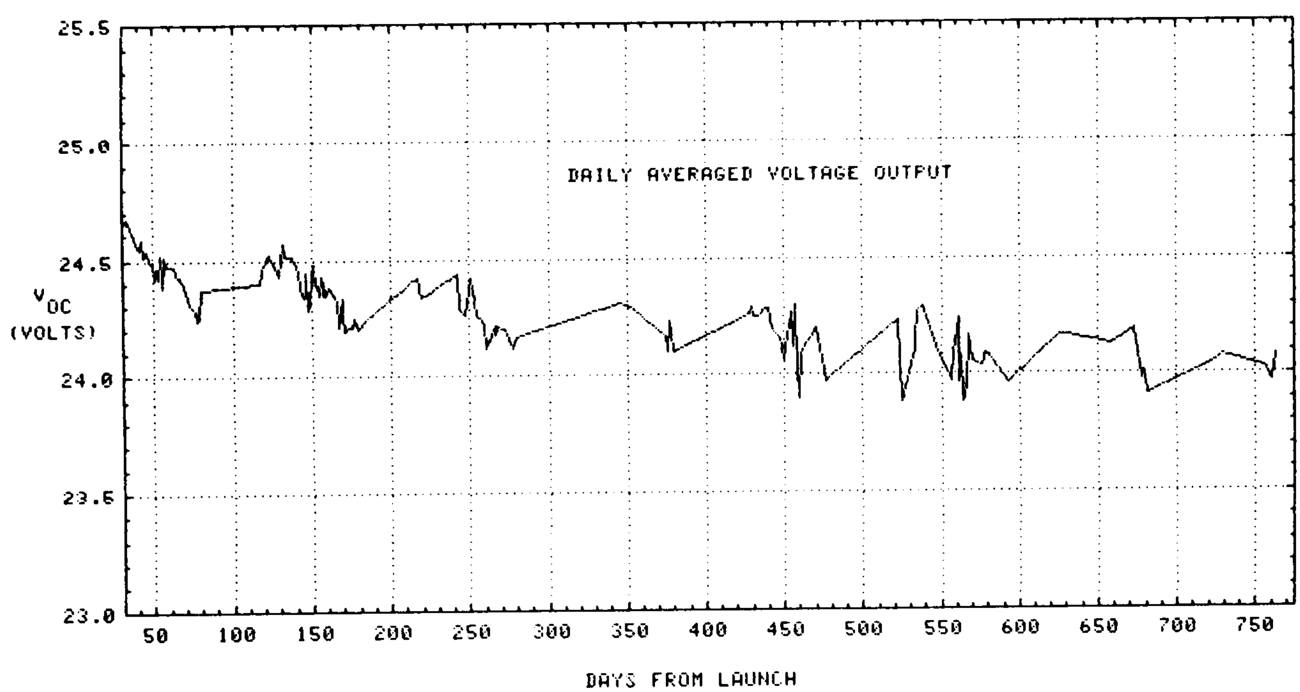

Figure 6

Fill Factor vs Days from Launch

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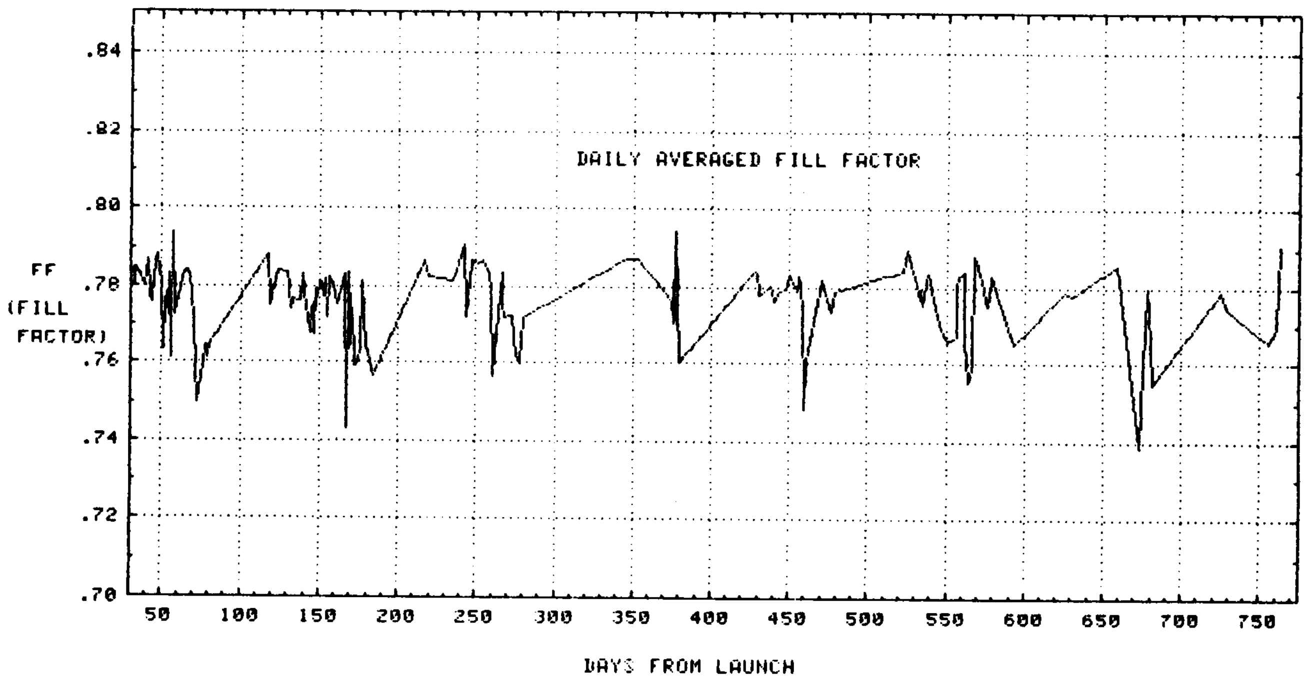

Figure 7

Series Resistance vs Days from Launch

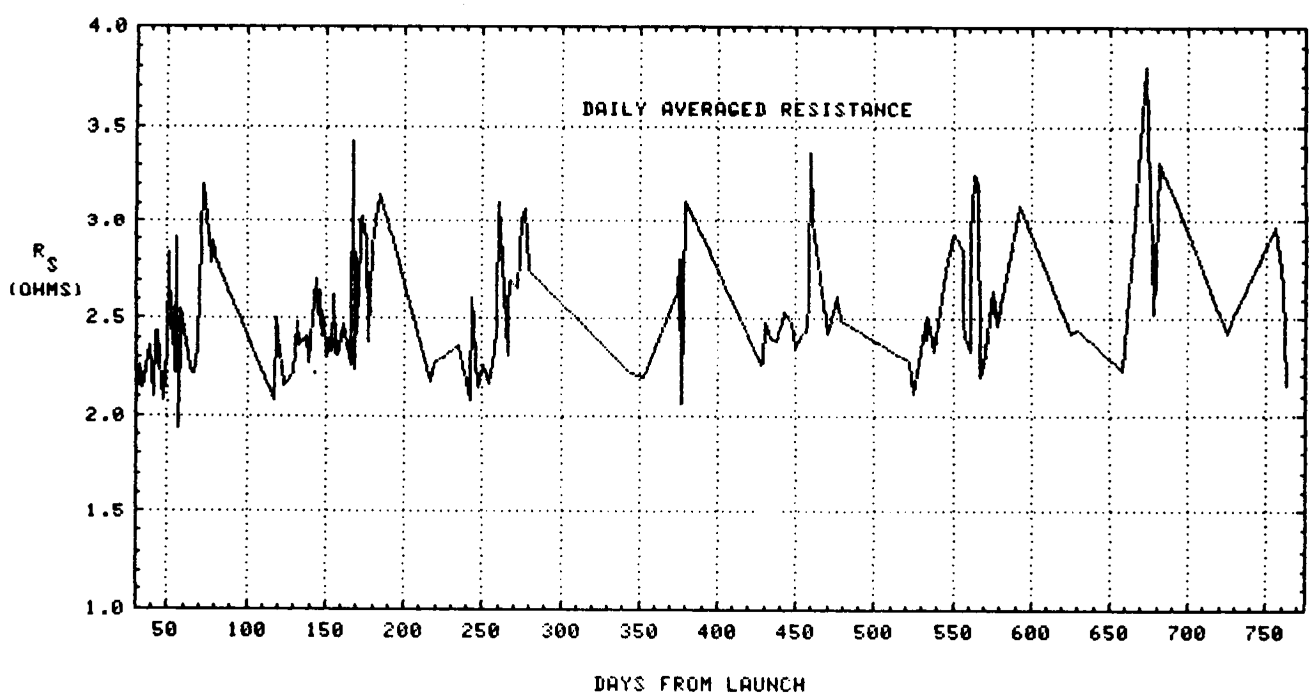

Figure 8